HIGH CURRENT ION BEAMS AT FRANKFURT UNIVERSITY

M. Droba, O. Meusel, U. Ratzinger, K. Volk, IAP, Frankfurt, Germany

Abstract

A new building for the physics faculty at the Goethe-University in Frankfurt is under construction including an experimental hall. The Institute of Applied Physics IAP has started the development of a high current ion beam facility consisting of a high voltage terminal (150 kV, beam current < 300 mA, ions H-, p, Bi+, singly charged noble gas ions), a 10 MV linear rf accelerator and a high current storage ring for 150 keV beams. The 150 kV terminal equipment is already ordered while the subsequent units are in the design phase. The storage ring will use a stellarator-like magnetic configuration which will provide new capabilities when compared to a traditional storage ring: the circulating direction is independent from the sign of the particle charge, the magnetic field level can be varied and influences the transverse beam dynamics mainly, the electrons can provide an efficient space charge compensation along whole circumference. The facility will allow high current beam investigations as well as experiments in the fields of plasma, nuclear and atomic physics.

150 KV TERMINAL

For the production of 150 keV high current ion beams, IAP is building up a 150 keV injector. It will be located in the new experimental hall of the institute.

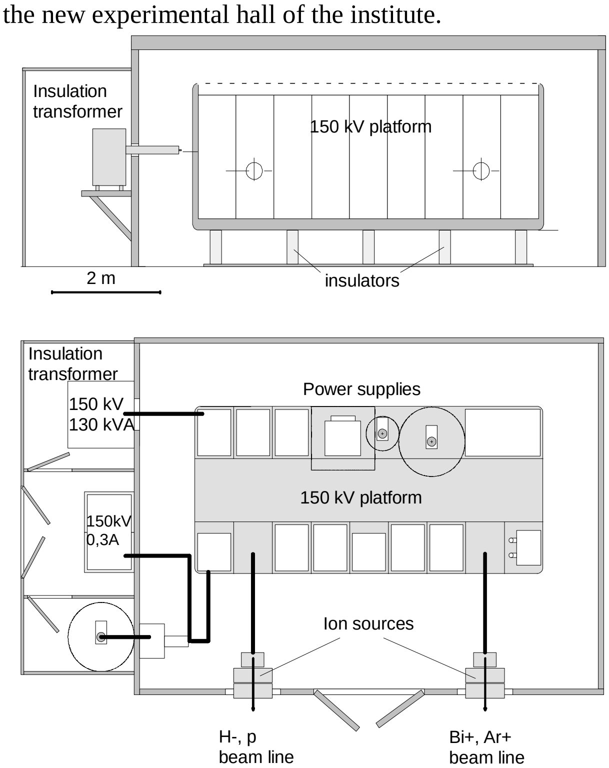

Figure 1: Schematic drawing of the high voltage terminal (view from the front and from the top).

The terminal is connected to a 150 kV insulation transformer, which is able to transform up to 130 kW electric power from ground to high potential. A 150 kV / 300 mA power supply is providing the terminal voltage. This will allow the extraction of ion beams with currents close to 300 mA in dc mode. For pulsed source operations with the extraction of beam currents higher than 300 mA a buffer capacitor, with a capacity of 3 μF, is implemented parallel within the high voltage power supply.

Figure 1 displays a schematic drawing of the terminal (side and top view). The length, width and height of the terminal are 10.5 m, 6.5 m and 4 m, respectively.

The high voltage platform is equipped with a large number of power supplies, primarily for the operation of arc discharge sources. For example, for the filaments a power supply with a maximum current of 1600 A is available, as well as a discharge power supply with a maximum current of 250 A.

The terminal has two source positions allowing the installation of two beam lines, one for H^-- and proton beams and one for a heavy ion beam line (Bi^+ or Ar^+). The whole housing is air conditioned including a humidity control. Nearby the terminal a container will be installed from where the terminal will be operated and controlled.

HIGH CURRENT STORAGE RING

A toroidal magnetic field configuration can guide ions and electrons along the ring orbit at the same time and by that way allows an efficient space charge compensation of the high current, low energy beams, for example by rest gas electrons.

The traditional ion storage ring consists of magnetic dipoles, quadrupoles, sextupoles where the distribution and the influence of electrons during high intensity ion beam operation can not be controlled and predicted easily. This gave one motivation to suggest and study high current rings with a main longitudinal component of the magnetic guiding field as commonly applied for the confinement of thermal plasmas (Tokamak, Stellarator…).

Methods and techniques from stellarator and plasma physics can be applied for these studies, however some differences are occuring. The ion beam phase space volume is small compared to the thermal plasma. A rapid beam motion along the central orbit occurs generating pronounced drifts. Also diffusion processes have to be studied for this case especially.

One attractive magnetic configuration to accumulate intense proton beams at an energy $W \sim 150$ *keV*, $\beta \sim 0.018$ and currents above $I \sim 10$ *A* could be the so called figure-8 configuration (Figure 2). Main parameters for our studies were choosen according to Tab. 1. The rotated magnetic field in such a configuration helps to cancel various drift motions (e. g. curvature drift, grad **B** drift, **E**x**B** drift) of the guiding centre.

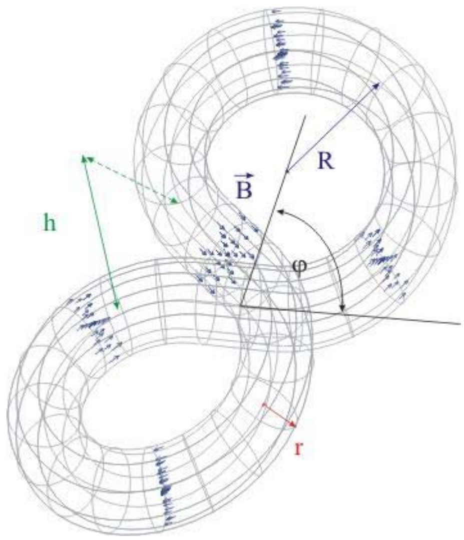

Figure 2: Figure-8 configuration

With respect to the lifetime of an injected p-beam the largest occurring cross sections are the resonant charge transfer reaction [1-5]

$$H^+ + H \rightarrow H + H^+, \quad \sigma(150\ keV\ p) \leq 10^{-21} m^2, \qquad (2)$$

as well as the reaction

$$H^+ + H_2 \rightarrow H^- + 2H^+, \quad \sigma(150\ keV\ p) \leq 10^{-23} m^2. \qquad (3)$$

Assuming a rest gas pressure of 10^{-10} *hPa* and an effective cross section of 10^{-22} m^2 per rest gas atom (H and highly charged ions on the percentage level only) one gets $n = 2.7\ 10^{11}\ m^{-3}$ and a free path length $l = 3.7\ 10^9$, life time $\tau = 6.8\ 10^2$ *s*. The electron proton cross section is very important at high beam intensities and is below 10^{-23} m^2 at energies above *10 keV*. It means that the electron motion has to be well controlled.

Table 1: Main parameters of figure-8 ring

Parameter	Value
Main radius *R[m]*	0.5
Minor radius *r[m]*	0.25
Vertical distance *h[m]*	0.6
Angle *φ[°]* between the straight sections	72°
On axis magnetic field *B[T]*	1-5
Rotational transformation	140°
Central orbit length *[m]*	6.3
Length of straight sections *[m]*	0.65

To study the complex beam dynamics various numerical computer simulations were done [11]. The magnetic field was computed by the numerical integration method (Biot-Savart law) for different coil configurations.

The radial dependence of the magnetic field strength on the curvature (R and straight sections, respectively) was studied in detail along the whole ring. The on axis variation of the magnetic field reaches 1% in the maximum.

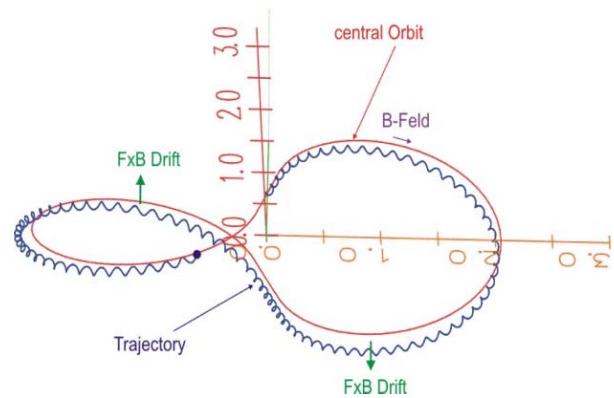

Figure 3: Drift compensation for a single particle motion in a Figure-8 stellarator.

The Finite Difference Time Domain (FDTD) method was used to simulate the short time behaviour (10 turns around the ring) of a single particle motion along magnetic field lines. Some physical parameters as the Larmor radius, frequency of oscillations and drift velocities could be verified. The motion without space charge effects and mirror charges was stable and drift compensation in the second half of the figure-8 system could be affirmed (Figure 3).

Another important point was the calculation of the Boozer[6,7] coordinate system and magnetic surfaces. The magnetic surface is a surface on which the common magnetic field line comes arbitrary close to every point of the surface. Existence of such surfaces is necessary for the stability of plasmas in stellarators [8].

To solve magnetic surfaces in figure-8 geometry the field line tracing calculation was done on the parallel cluster of the *Computer Science Center* (CSC) in Frankfurt. Here a 10000 step calculation along the ring was chosen, this means 0.6mm per step. For the efficient mapping of a whole surface 30 rotations around the complete ring were done.

An example of a cross-sectional distribution of field lines in a bending arc of the ring is shown by Figure 4. Point (0,0) defines the geometrical axis while the magnetic axis has moved to the right (about 2 cm) in horizontal direction. 30 points per surface result from 30 runs around the whole ring. It is obvious that for bigger surfaces additional points are still needed for efficient mapping in that case.

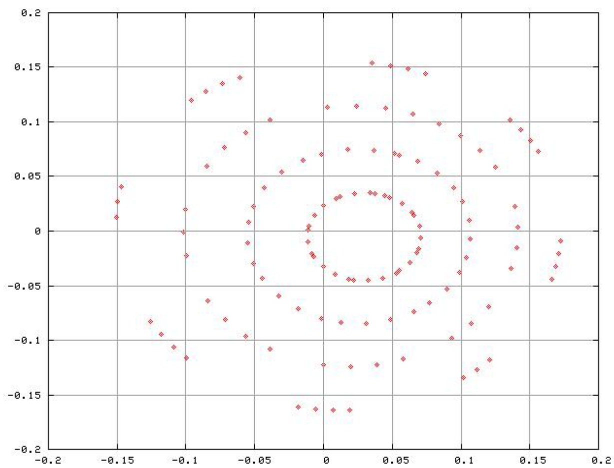

Figure 4: Results of field line tracing simulations for 4 magnetic surfaces in one cross section of one bending arc of Fig.2.

After the simulation run post-processing of data fields was done. The poloidal rotation of the magnetic field line amounts to 140° per turn for the calculated geometry. Also a shear of magnetic surfaces was observed in some parts. This fact is very important for the transversal stability of stellarators [9-10].

Additional parameter settings of the new coordinate system (based on magnetic surfaces) were evaluated. For the visualization and better understanding the 3D graphical code was written. After applying the NURBS(*Non-Uniform Rational B-Splines*) – method on the computed data one magnetic surface is shown by Figure 5.

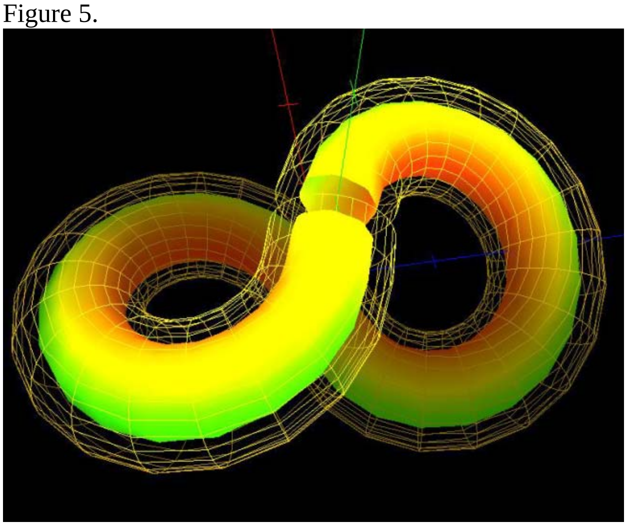

Figure 5: Magnetic field on a magnetic surface. The amplitude falls from red to green.

Here, the wire-frame represents the vessel of the ring with the example of one magnetic surface inside. Colour coding was used to show the amplitude of the magnetic field on that surface. Higher field values are located on the side pointing to the centre of the curvature.

Next studies will be concentrated on injection studies and space charge calculations. Using of **E**x**B** drift techniques in pulsed electric fields (*E ~ 25kV/cm*) could help to inject the particles into the ring. The injection part would be positioned in the straight sections with crossed E and B fields.

An algorithm for the guiding centre approximation in the Boozer coordination system will be used to simulate the space charge behaviour.

CONCLUSIONS AND OUTLOOK

IAP designs a high intensity, low energy ion beam facility, which may be realized at the new building of the physics faculty of Frankfurt University. A 150 kV, 300 mA high voltage terminal is under construction. A Figure-8 stellarator like configuration seems promising for the storage of intense low energy ion beams. Multi particle simulations are planned in the future study of the accumulator ring. Here an efficient parallel version of a PIC-code is in preparation. Also a test electron ring for dynamics studies is discussed at IAP. The differences between plasma and beam physics and technical consequences have to be studied in detail.

REFERENCES

[1] J. T. Park, et al., Phys. Rev. A 14(2), August (1976), p.608.
[2] G. W. McClure, Phys. Rev. 148(1), August (1966), p.47.
[3] V. Franco, B. K. Thomas, Phys. Rev. A 4(3), September (1971), p. 945.
[4] Y. Kim, M. E. Rudd, Phys. Rev. A 50(5), November (1994), p.3954.
[5] M. B. Shah, et al., J. Phys. B 20(14), July (1987), p.3501.
[6] A. H. Boozer, Phys. Fluids 25(3), March (1982), p.520.
[7] X. Bonnin, et al., 30th EPS Conf. on Contr. Fusion and Plasma Phys., St. Petersburg, 7-11 July 2003, ECA Vol.27A, P-4.10.
[8] V. D. Shafranov, Phys. Fluids 26(2), February (1983), p.357.
[9] W. W. Lee, et al., Phys. Rev. Letters 43(5), July (1979), p.347.
[10] P. N. Guzdar, et al., Phys. Rev. Letters 40(24), June (1978), p.1566.
[11] M. Droba, et al., Annual Report 2003, High Density Physics with Intense Laser and Ion Beam, GSI (2003).